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Improvement in policy and proactive interconnection procedure for renewable energy expansion in South Korea

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ABSTRACT

This paper presents the steps taken by the Korea Electric Power Corporation (KEPCO), the nation's only utility, to overcome limitations involved in increasing renewable energy penetration in an effort to support the government's movement for renewable energy expansion. While the government proposes reducing carbon dioxide emissions by 37% of the Business As Usual (BAU) value by 2030, which is about 315 million tonnes, it has improved energy policies for developing and deploying renewable energy technologies. To facilitate the integration of renewable energy into the future Korean power system, the government has announced a guaranteed interconnection policy for renewable energy sources under 1 MW. Based on this movement, the following measures have been enacted. First, examination of the hosting capacity of the current power system has been initiated to streamline the interconnection process for the distributed renewable energy sources and to reinforce the transmission and distribution network in a proactive manner. Second, to comply with reliability performance standards, an efficient planning procedure has been established for determining the optimal location and size of a renewable complex. To proceed with interconnection requests without delay, a prototype of a Renewable Energy Map (REM) based on PSS/e and Python has been developed. This tool facilitates more practical impact studies by incorporating capacity factors of renewable sources. In addition, it automates the screening process for determining suitable interconnection buses and feasible options for grid reinforcement. This tool is a step toward realizing the twin visions of "G-Platform" and "Carbon Zero" projects in Jeju Island." These efforts, which have been initiated in response to the Paris Climate Change Accord of 2015 and the 23rd Conference of the Parties 2017, aim to increase renewable energy from 7% to 20% of the total generated energy in Korea by 2030.

1. Introduction

The power system in South Korea is heavily dependent on primary sources such as nuclear, steam, and coal plants because of the high load demand relative to the size of the country. From spatial and economic perspectives, the contribution of renewable energy has been insignificant thus far, and interconnection among the different types of power systems has raised grid issues. Accordingly, among Organization for Economic Cooperation and Development (OECD) countries, Korea has been ranked first for increasing greenhouse gas emission rates from 1990 to 2014 and sixth for greenhouse gas emissions (690 million tonnes) in 2015 [1–3]. Following the Paris Climate Change Accord in 2015 and the 23rd Conference of the Parties 2017 (COP23), the Korean government has taken the stance of reducing greenhouse gases through increased penetration of renewable energy sources, thus ushering Korea into a new era for the renewable energy industry [1,4]. As a result, the government has proposed a policy for reducing carbon dioxide emissions by 37% from the current Business As Usual (BAU) value, which is about 315 million tonnes [1,4]. Within 315 million tonnes, the generation sector utilizes 19.4%, which is the largest of all categories. Therefore, increasing renewable penetration must be optimized to achieve this goal.

The total capacity of renewable energy sources is currently about 15 GW [5]. Although the renewable energy capacity in South Korea is behind that of European nations, China, and other countries, it has shown a consistent annual increase of 11,860 MW in 2014 to

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13,729 MW in 2015 and 13,846 MW in 2016 [6–9]. The Korean government put forward the 3020 Project, which presents its objective for increasing the proportion of renewable energy source penetration from 7% to more than 20% of total generation amount by 2030 [5]. To achieve this goal, approximately 60 GW of renewable energy facility is required.

In order to increase the various types of renewable source penetration, several studies have been undertaken that present feasibility studies of solar energy usage in Korea [10,11], the potential of ocean and tidal power [12–14], and the feasibility of offshore wind energy [15]. Additionally, efforts have been made to develop a forecasting model for renewable energy supply [16] and to evaluate the economic value of investments in the wind power energy sector [17]. Domestic studies have been conducted to determine the optimal renewable fraction and cost in certain grids [18], to observe economic feasibility maps for 17 cities in Korea for potential interconnection points [19], and to obtain statistical data on the efficiency of different types of renewable sources in Korea [20].

This paper presents the steps undertaken in three key areas in an effort to achieve this goal in Korea. First, the government's efforts toward improving policy and support schemes for the diverse expansion of renewable energy market growth are briefly introduced. An appropriate and effective support scheme and fair interconnection policies have been continuously improved over time. Next, the Korea Electric Power Corporation (KEPCO), the nation's only utility, will introduce efforts to fully explain the hosting capacity for the current power system structure and facilities to efficiently plan for the grid reinforcement without public opposition. Finally, the efforts of KEPCO and associated universities for developing a Renewable Energy Map (REM) will be introduced. REM is required to identify the optimal location and sizing for a renewable complex that does not violate the reliability standard. Planning for the hosting capacity of the current power system is necessary for successful interconnection because it facilitates the prediction of accurate generation in different time intervals, the determination of the optimal location for interconnection, and the installation of a system that complies with the grid code.

The government has acknowledged the need for necessary change in a support scheme for renewable energy penetration. The official record including public utilities in 2016 shows that renewable energy accounted for 7.24% of the total energy generated, or 40,656 GWh, as shown in Fig. 1 [7]. The increase in penetration rate is promising; however, an insufficient planning support scheme resulted in a biased participation of certain renewable sources such as waste energy. Although the capacity of photovoltaic (PV) energy is the largest among all types of renewable sources, the amount of generation is dependent on the waste energy, as shown in Fig. 2 and 3 [7]. This is far removed from the government's intention of focusing on increasing PV and wind penetration. Thus, the government has presented a vision to further support wind and PV energy so that they will become major renewable

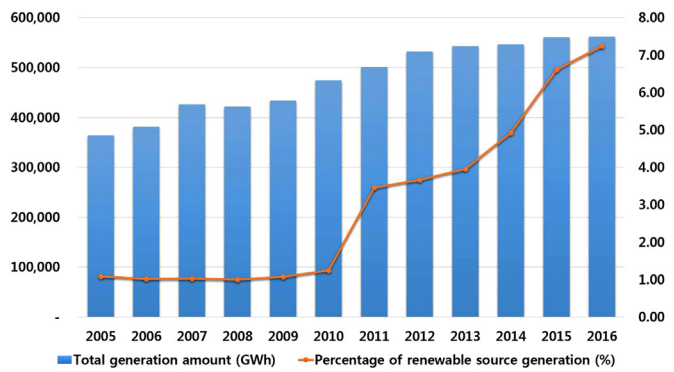

Fig. 1. Total amount of generation and the proportion of renewable generation in Korea.

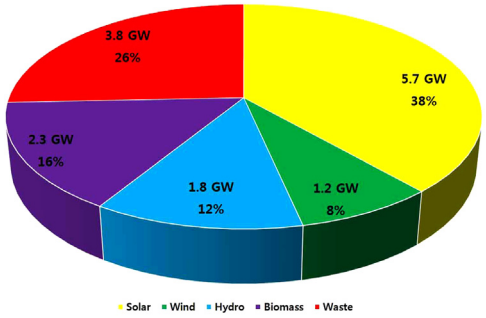

Fig. 2. Ratio of each type of renewable energy generation in 2016.

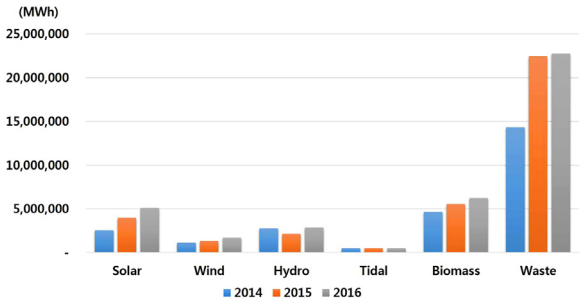

Fig. 3. Comparison of each type of renewable energy generation in 2014, 2015, and 2016.

power sources. One example of this support is the establishment of a large wind farm on Jeju Island [21]. Accordingly, the government aims to stop constructing more plants for waste energy and will continue to construct more PV and wind energy systems until it can account for 85% of the total renewable energy capacity, at about 50 GW [5].

Furthermore, the government has taken initiatives by proposing the “Guaranteed interconnection of renewable energy sources under 1 MW” plan in 2016 to invigorate the renewable energy industry by redesigning the traditional utility infrastructure [1,22–24]. Although this policy has dramatically increased the requests for renewable generation interconnection, the processing the interconnection has been delayed owing to a lack of understanding of the hosting capacity. The Korea power system must be analyzed to determine the correct hosting capacity of the current power system. This will minimize the cost of the interconnection and grid reinforcement and will enable compliance with the grid code. The interconnection and the grid reinforcement process is a very delicate and controversial issue in Korea because of the convoluted and slanted structure of the power system. The public has voiced strong opposition against the additional construction of power facilities, with zero tolerance for poor power quality [22–24].

A prototype of the REM is introduced in the present study. This map will be used to accept interconnection requests efficiently in the future and to determine interconnection locations and an appropriately sized renewable complex that fully utilizes the existing power system infrastructure [25,26]. In particular, this REM will be useful for determining the acceptable locations and sizing for wind and PV plants. The program is capable of analyzing loading, voltage deviation, and fault current contribution such that estimation of the hosting capacity is possible. By using the REM, a renewable interconnection zone known as “G-Platform” can be allocated to enable the construction of a renewable complex known as “Open Green Grid.” This measure will contribute to the transition from scattered and unplanned renewable interconnection to integrated interconnection [24]. In addition, the “Carbon Zero” project in Jeju Island can be initiated. Because approximately 2 GW of wind power complex is expected, careful interconnection must be conducted by utilizing the REM for maximum benefits. The renewable complex is continuously monitored and controlled to comply with the

grid code and to support the power system stability rather than providing uncertainties.

The rest of this paper is organized as follows. Section 2 presents a brief history of renewable energy penetration and the renewable energy support scheme and policies offered by the government. This section also addresses problems and improvements in policy. Section 3 presents the current problems experienced by KEPCO in renewable interconnection procedures and efforts in determining the hosting capacity of the existing power system. Section 4 presents efforts in developing an REM to help KEPCO determine the location and sizing of a renewable generation interconnection. Section 5 presents KEPCO's visions to increase and extend renewable penetration and to present projects that enable visions such as G-platform, “Renewable monitoring center,” and the Carbon Zero project on Jeju Island. Section 6 presents the conclusion of this paper.

2. Renewable energy interconnection policy

2.1. Renewable energy implementation support scheme in Korea in the past, present, and future

Following many European countries, the Korean government launched a Feed-in-Tariffs (FiT) system in 2002 to encourage renewable interconnection [1,8,27]. The government was able to manage the market with FiT in the program's early days because the number of contractors and the market size were relatively small, and the eligibility of the subsidy was as high as 500 kW. However, the policy was changed in 2012 to a Renewable Portfolio Standard (RPS) because of the burden it placed on government expenditures [28–34]. Two main reasons can be identified for the transition to the RPS system. First, the number of private contractors and the capacity of renewable power plants have increased dramatically over time. This created difficulties for the government in managing and securing each contractor, which gradually changed the market structure. Second, the subsidy announced by the government was fixed under FiT, which did not reflect the new market status. Eventually, the government changed the policy to RPS to shift the responsibility regarding subsidies to the affiliated national power companies to negotiate with contractors.

According to the RPS, utilities larger than 500 MW must generate 2% of the total generation from renewable energy sources by purchasing from private contractors or building renewable power plants. The percentage must increase by 0.5–1% every year to reach up to 10% by 2023 [28,35]. In particular, the RPS was assigned to 13 large public and private power companies. Renewable Energy Certificates (REC), which reflect the progress of government in employing PV and non-PV energy, are listed in Tables 1 and 2 [1].

This plan has benefitted the government because it is more financially sustainable and has an easy generation forecast. However, because varying costs make it difficult for small corporations to compete, not all renewable sources can participate equally in the market. Among the types of renewable energy employed by using the RPS in 2014, biomass usage was 32.2%, and usage of fuel cells, PV, and wind were 14.1%, 11.6%, and 6.4%, respectively [1]. Even though the annual PV capacity is significantly larger than that of waste energy, as shown in Fig. 4, more than 60% of electricity is generated from waste and biomass energy. The current situation does not meet the government's aim of encouraging a diverse spectrum of renewable energy sources. Of the total renewable energy capacity, about 46% of renewable sources were selected for the RPS, as shown in Fig. 5. About 3289 MW from PV was selected for the RPS, which is about 43% of all selected renewable sources [1]. The RPS has produced a relatively large increase in PV penetration, although the incentive policy and environmental issues have prohibited private contractors from making a profit. Unplanned installation has become concentrated in certain areas, which has led to public opposition as well as an unstable REC price caused by a competitive market.

At the early stage of the RPS, contractor profit was highly dependent on the System Marginal Price (SMP), which is also closely related to the price of oil, as shown in Fig. 6 [1]. The REC price was also determined without a standard, which caused unstable profits for contractors and led to a decline in PV penetration. Therefore, a significant amendment to the renewable support scheme is required to further expand the diverse renewable energy market.

Table 1
REC value for PV.

REC value	Location	Condition
1.2	land	Under 100 kW
1.0	land	100 kW ~ 3000 kW
0.7	land	Above 3000 kW
1.5	Within buildings	Under 3000 kW
1.0	Within buildings	Above 3000 kW
1.5	Float on water	–
1.0	Residence	–
5.0	Integration with ESS	–

Table 2
REC value for non-PV renewable energy.

REC value	Type of source
0.25	IGCC
0.5	Waste and Landfil gas
1.0	Hydro, wind, bio energy, gas tide, EV
1.5	Offshore wind
2.0	Fuel cell
2.0	Offshore wind (above 5 km) and thermal
Up to 5.5	ESS with wind energy

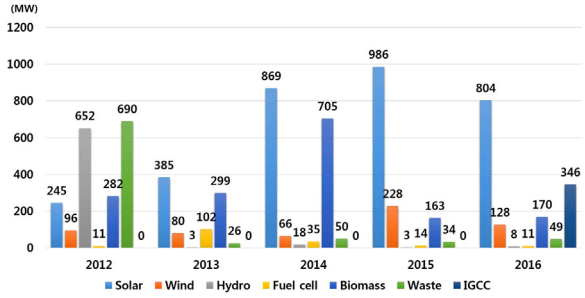

Fig. 4. Renewable energy source implementation status from 2012 to 2016.

2.2. Support scheme improvements and efforts regarding renewable energy integration procedure

To balance and emphasize the usage of diverse renewable energy

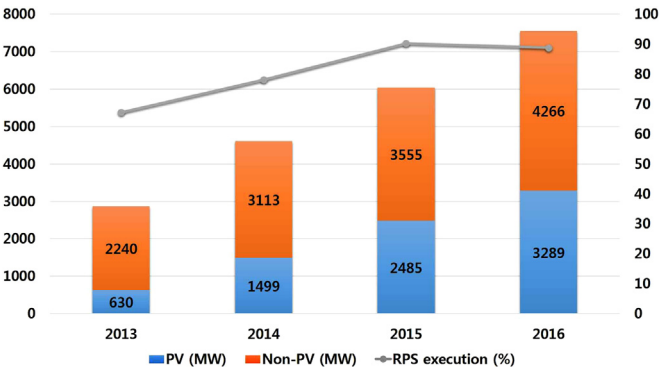

Fig. 5. Accumulated capacity of renewable sources selected for the RPS.

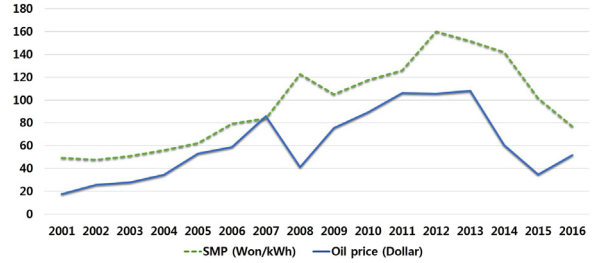

Fig. 6. SMP price tendency according to the national oil price in Korea.

generation, the following attempts have been made by the government to enhance the RPS system.

(1) Improvement in renewable energy market structure
(2) Financial support from the government
(3) Faster interconnection procedure

The guarantee of profit is critically important to persuade utilities and contractors to implement renewable energy sources. As shown in Fig. 5, the first year of the RPS yielded a 65% success rate, whereby utilities performed their obligations [1,35]. Through multiple revisions, power companies must have a contract for purchasing electricity from renewable sources resulting from a combination of SMP and REC for approximately 20 years rather than fixing the price through SMP only. This initiative prevents subsequent issues resulting from severe fluctuations triggered by the renewable market, which is continuously affected by oil prices. The unification of the renewable market has also been initiated. In the early stages of the RPS, the renewable market was categorized into PV and non-PV sources, whereas REC can now be traded without source classification. This has allowed utilities to execute the RPS without excessive complexity. If the PV is integrated with the energy storage system (ESS), additional REC is given to private contractors. Improvements in supporting non-PV energy sources have also been made by increasing the REC weighting factors on tidal, geothermal, and hydrothermal power up to 2.0 [1,35]. To expand PV use, the government has increased incentives for PV panels to be installed in houses and schools and has decreased the installation cost to enhance and stabilize the PV market. PV energy usage has increased for large buildings, and private contractors are also able to sell power under 10 MW of PV energy.

In 2017, the government committed $70 million toward installation costs for renewable energy facilities for high-efficiency houses and buildings. About $60 million has been earmarked for maintaining renewable generation facilities, and about $300 million will be used to subsidize utilities to purchase electricity produced by PV and wind energy. In addition, $1 million dollars will be assigned to R&D centers to develop more advanced technology for renewable energy [1].

The government has implemented a faster interconnection procedure by shortening the duration of system reinforcement. In addition, it has proposed a guaranteed interconnection of renewable energy sources under 1 MW and is also considering guaranteed interconnection of renewable energy sources above 1 MW [1,22–26]. Issues remain with interconnecting sources larger than 1 MW; however, the policy likely will shorten the interconnection procedure as well. More detailed information on the interconnection procedure will be discussed in later sections.

Overall, the performance of utilities between 2012 and 2014 has improved regarding obligations met. As shown in Fig. 5, the RPS performance improved from 64.7% to 78.1% in 2014, and the official record in 2015 is 90.2% [1]. The RPS system, with multiple corrections, allowed for expansion of the renewable energy investment, the fostering of domestic industry, and cost reduction. Five years of the RPS has led to an increase of more than 7.7 times the renewable capacity of

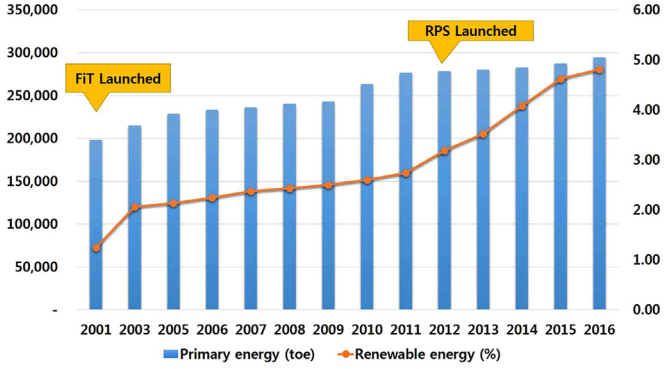

Fig. 7. Renewable energy penetration rate in Korea from 2001 to 2015.

the renewable energy sources installed in ten years of FiT. PV generation in 2014 increased 2.4 times compared with the previous year, from 602 GWh to 1427 GWh. Non-PV generation in 2014 increased 1.8 times compared with the previous year, from 3994 GWh to 7260 GWh [35]. As shown in Fig. 7, the renewable energy market for both trading REC and self-generation service continues to increase, and the RPS system has helped to increase the tonnes of oil equivalent (TOE) to 4.81% in 2016 [7]. The government has proposed an increase in RPS percentages from 4.5% to 5% by 2018 and from 9% to 10% by 2023, which will allow more usage of renewable energy. Accordingly, the number of utilities participating in the RPS increased to 18 companies in 2016 [1]. The government recently published a report for an overall capacity growth on nuclear, coal, liquefied natural gas (LNG), renewable energy, gas, and water pump energy for forecasting the minimum amount of renewable capacity excluding behind meter sources to generate 20% of the total generation by 2030. As shown in Fig. 8, the growth of non-renewable energy sources will barely increase or even decrease, whereas the renewable energy capacity will increase approximately 4 GW every year until it becomes 30% (60 GW) of the total generation capacity. Ultimately, the capacity will achieve 20% of total generation amount, which is the target of the 3020 project [5].

The promising improvements in Korea's renewable energy policy are attributed to the enthusiastic initiatives extended by the government. Although selection of appropriate support schemes such as FiT or RPS are important, the willingness to improve overall policies appears to be more important. European countries who share targets by their National Renewable Energy Action Plans (NREAP) from 2010 to 2020, such as Bulgaria, the Czech Republic, Greece, Hungary, Portugal, Spain, and the Netherlands, have failed to meet their targets owing to a lack of support schemes from their governments [8]. Specifically, retroactive measures, lack of fair and independent regulation, lack of transparency on the connection procedure, cancellation of support schemes, long grid development process, and reliability issues are the main barriers faced by the aforementioned countries. Most countries that achieved their goals share similar support schemes as those that failed; thus, the

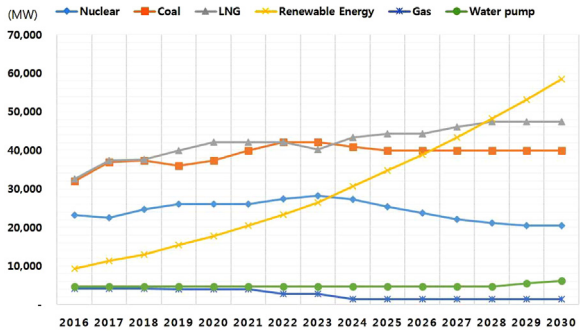

Fig. 8. Projected overall energy capacity growth from 2016 to 2030 in Korea.

support scheme is only part of the driving force for a prosperous renewable energy industry.

3. Renewable interconnection procedure and hosting capacity

3.1. Issues with interconnection to the existing system

The planning of conventional power generation in Korea based on nuclear and coal power plants normally includes 5–10 years of service. This rarely causes problems with transmission planning because transmission lines are generally expected to be developed according to predetermined generator planning [22]. However, renewable plant planning is difficult to integrate in conventional system planning because of its convoluted process of determining the location, which must comply with local regulations, in addition to estimation of the appropriate capacity, which has various sources of uncertainty. The problem includes fluctuating characteristics of renewable sources and frequent changes in business plans and capacity changes, which make it difficult to establish solid system planning.

A policy regarding interconnecting renewable energy sources has not been clearly documented thus far because of various grid issues and their system reinforcement procedures. Therefore, great difficulty remains in granting renewable energy source interconnection to renewable generation contractors who are eager to connect to the grid. Furthermore, for the Paris Climate Change Accord in 2015, the government proposed a scheme of “Guaranteed Interconnection of Renewable Energy Sources under 1 MW” in 2016 to invigorate the small-scale renewable energy market. Although the updated interconnection policy for renewable energy is still in development, contractors began to request interconnections of a total of 1789 MW immediately after the government's announcement in December 2016 [1,23].

Apart from policy issues, other problems have been reported in the process duration. The current climate requires a longer time for interconnection. It is expected that technical review, interconnection construction, distribution, and transformer construction together take approximately 11 months [23]. Interconnection policy regarding generation larger than 1 MW affects the grid stability because most renewable interconnections are expected in the southwestern part of Korea, where the grid is relatively weak. Detailed studies are required on the interconnection of generation larger than 1 MW in preferred areas for renewable connection because current studies show that system reliability issues can occur. Therefore, it has been very difficult to support the grid reinforcement when renewable generators larger than 1 MW are connected to the grid.

Currently, renewable generation interconnections of 65% of the request of 1789 MW is possible. Of these, 41% could be connected immediately upon construction, and 24% could proceed followed by short-term reinforcement of the grid [23]. However, the remaining interconnection requests (35%) may take longer than expected because several new substations must be constructed to successfully interconnect the remaining renewable sources, which will take at least six years. The number of requests from private corporations for interconnecting renewable sources is expected to increase dramatically in the near future.

3.2. Mitigation measures

Currently, the capacity limit policy in Korea for renewable interconnection has been limited to 25 MW per transformer, considering possible failures. As a mitigation measure, the interconnection capacity has increased to 50 MW so that 35% (620 MW) of the waiting interconnections can to be brought into the system without being overdue [23]. Further, an amendment regulation in 2014 increased the maximum capacity at a 22.0/154 kV substation from 40 MW to 75 MW. Because it is expected that most renewable interconnections will be made in these designated areas, interconnection capacity will increase up to 100 MW in the near future. However, increasing the capacity of renewable interconnections raises certain reliability issues when the transformer fails or the system encounters sudden voltage deviation. Negotiations must be well coordinated between the utility and the contractors as to whether to operate renewable plants with curtailments under certain contingencies that endanger the grid reliability. Furthermore, the influence from power congestion caused by power angle deviation and reactive power insufficiency must be analyzed. If there a problem occurs, mitigation measures such as transmission reinforcement, effective interconnection methods, appropriate location investigation, and reactive power compensator construction must be considered.

Renewable interconnection planning will be conducted every two years to reflect any changes required in the middle of interconnection planning. Moreover, frequent system planning enables synchronization of the operations of newly interconnected renewable plants and the construction of system reinforcement. If system reinforcement takes longer than expected, contractors must be informed that they need to operate under certain conditions. For example, renewable plants on Jeju Island should operate with constraints until the completion of high voltage direct current (HVDC) No. 3, which transfers power to the mainland. Because the structure of the generation mixture changes from a few large-scale plants to numerous small-scale renewable plants, appropriate planning for short/long-term transmission/transformer facilities must be performed. Along with the expansion of substation facilities, a new type of transmission line, the aluminum conductor composite core (ACCC), has been used to significantly increase the transmission capacity.

3.3. System reinforcement allocation and system constraints

To account for newly interconnected renewable generators in the planning stage, it is necessary to establish a firm policy to determine which party should bear the costs of transmission reinforcement or how costs should be allocated when power system instability occurs. The most recent policy states that KEPCO is fully responsible for transmission reinforcement. Although KEPCO has decided to bear the network reinforcement cost for interconnecting generation under 1 MW, interconnecting generation larger than 1 MW is still a controversial issue in terms of which party should be responsible for the grid reinforcement costs. Various factors must be considered to efficiently and fairly allocate costs for both parties without conflicts. Details of the reinforcement criteria are still in development; however, KEPCO is willing to bear reinforcement costs to enlarge the renewable energy market and to reduce system constraints. Numerous literature surveys and analysis on policies in Europe and the United States state that it is important to maintain sustainable policies [8,36]. As mentioned previously, many European countries that participated in NREAPs were not able to achieve their goals because the support schemes were insufficient and because regulatory revisions and retrospective applications have critically damaged renewable energy utilities [8,37,38]. The insufficient governmental support notwithstanding, most of the system operators in European countries still use the “shallow” policy and have considered switching to the “deep” policy only as a last resort [8,39]. Countries such as Australia, Panama, Brazil, the Philippines, and Egypt use the “shallow” policy for encouraging renewable plant interconnection [40–42].

However, most of the utilities in the United States have chosen the “deep” policy, where contractors are more responsible for interconnecting renewable plants to the grid and for consequent grid reinforcement [36,43–46]. Each of the utilities adheres to the Small Generator Interconnection Procedure (SGIP) based on its own philosophy while sharing the concept that contractors can profit from customers directly or from transmission usage fees.

Based on this information, it is difficult to decide which policy to

choose. It is still the general opinion that choosing the “deep” policy in Korea would be impractical because contractors are discouraged if the initial investment is too high and if the procedure is complicated and extensive. This may result in a bottleneck in achieving targets proposed by the government for 2030. Therefore, if KEPCO further maintains a sophisticated policy for determining the optimal price for renewable energy that benefits both contractors and KEPCO, KEPCO is willing to select a “shallow” policy even if the cost of system reinforcement is high [26].

3.4. Proactive interconnection procedure

The mission of the future Korean power sector is to secure transmission capacity within appropriate levels of reliability and economy in response to changes in the environment. However, under the circumstances in which the area of land is small and its price is skyrocketing, construction of transmission and distribution facilities as planned faces severe public opposition. Based on literature surveys of proactive planning approaches [47–51], KEPCO has attempted to establish an REM to sufficiently acquire data for a nationwide study of renewable energy unit interconnection capability [26]. Through analysis of the available capacity and the development of a transmission map, it is possible to improve the reliability of the system when renewable energy equipment is interconnected to the existing grid. In addition, all acquired data will be disclosed to the public so that future contractors fully understand the demand for renewable generation.

Competitive Renewable Energy Zones (CREZ) in Texas are designated for transmission reinforcement in order to develop a competitive wind energy market and to efficiently generate a renewable source in northwestern Texas owing to its abundant wind resources [52]. The Electric Reliability Council of Texas (ERCOT) revised the interconnection procedure systematically for step-by-step interconnection and reinforcement. To reinforce the system for wind power interconnection, ERCOT measured the capacity factor at potential wind power locations in northwest Texas and evaluated the system reliability using average and maximum values as well as their ramping rates. Based on this information, ERCOT established a system reinforcement plan to increase the capacity of the system. Because the CREZ are remote from the metropolitan area, four phases in reinforcement were used to increase the grid capacity from 2.4 GW to 7.5 GW.

The Electric Power Research Institute (EPRI) has developed a streamlined hosting capacity method for efficient and fast interconnection and reinforcement [47]. This method estimates the capacity of the system prior to the reinforcement, making it possible to predict the expected increase of renewable sources after a particular grid reinforcement. Then, the change in the capacity of the reinforced system is evaluated based on three different ratings of the American National Standards Institute (ANSI). This procedure is automatically performed and evaluated according to the changes in the grid environment with statistical data of interconnecting points. As a result, it is possible to evaluate the capacity according to regional- and capacity-specific scenarios. This improves the efficiency of system analysis and facilitates more reasonable decision making in preventing unnecessary reinforcement costs and interconnection delay.

TransGrid in Australia has also undertaken a grid capacity mapping project by identifying potential renewable energy hubs [53]. This enhances the efficiency of the system and reduces the interconnection cost by gathering renewable connections in one hub rather than connecting to individual hubs in scattered forms.

To summarize, understanding the current capacity and setting up various scenarios for potential locations of renewable plant interconnections must be conducted to calculate the accommodation capacity of the grid can when renewable plant interconnections are increased gradually. System operators should make this information public through visual maps that can help contractors select optimal connection points. The capacity disclosure should provide numerical values in addition to diagrams that reveal geographical and power system information.

Current system planning methods in Korea do not accurately reflect the characteristics of renewable generation; as a result, it is difficult to ensure the accuracy and reliability of system planning. To efficiently improve the planning of renewable power, it is necessary to modify the current system planning methods. In the distribution system, the introduction of smart inverters will enable the grid capacity to be calculated as a maximum/minimum range rather than an exact value, and changes can be applied to the conventional grid stability assessment method. In addition, if a promotion policy for renewable generation is firmly established, the number of applications for generator connection is expected to increase significantly. Thus, from a long-term perspective, changes in the current interconnection procedures and system planning procedures are urgently required. To implement such a proactive approach in system planning, KEPCO has decided to focus on the effective capacity for potential renewable energy to evaluate system reliability and, accordingly, the utility of various system reinforcement scenarios.

The acquisition of transmission information of interconnection capability begins with substations under 154 kV, which have expanded regionally. The information includes contingency analysis, requests for additional breakers among substations, long-term loading rates for transmission and distribution equipment, and fault current contribution and its impact. In the case of opening transmission information of renewable source interconnection to the public, it is necessary to secure an objective and reliable analysis result for fair and transparent procedures.

3.5. KEPCO's power system planning standard prior to accommodating renewable source penetration

KEPCO has focused on renewable capacity analysis for REM development by fully understanding the existing transmission network to allow for the construction of additional transmission facilities by region [24]. First, power grid area classification and inter-regional grid transmission line selection must occur. Second, analysis of system effects must be conducted in case of contingencies such as overload, fault current, or transient stability.

The process of reviewing the transmission construction outline is divided into three steps, as shown in Fig. 9. Although 1789 MW of renewable energy has been requested for interconnection, the system operation point is determined by processing various operating strategies with existing and renewable generators.

In step 1, the availability of short-term connections by region/substation is verified, whereby the confirmation of spatial margins and possible interconnecting capacity status are investigated. In addition, preliminary confirmation for grouping substations from three to five is initiated.

In step 2, the possible capacity for each substation is reviewed. As

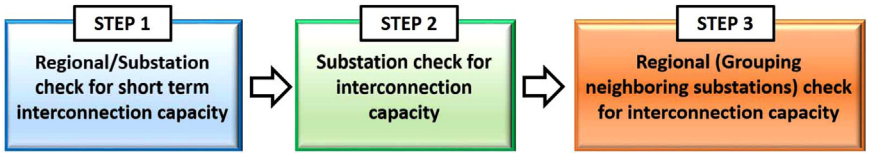
STEP 1
Regional/Substation check for short term interconnection capacity
STEP 2
Substation check for interconnection capacity
STEP 3
Regional (Grouping neighboring substations) check for interconnection capacity

Fig. 9. Transmission assessment procedure operated by KEPCO.

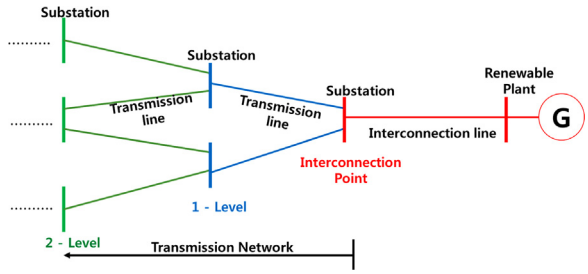

Fig. 10. Assessment of possible hosting capacity two levels away for each substation.

shown in Fig. 10, a review of generators two levels away is initiated based on the interconnecting substation. All 154 kV substations are interconnected with a 500 MW generator. A preliminary study is performed by using PSS/e based on the pre-determined 2029 power system database [24]. This process reviews the potential interconnection points for renewable plants by observing the impacts from remote generators two levels away at most that are connected with the 154 kV level under peak and off-peak cases. If the case cannot be resolved, the power from the interconnected generator is lowered by 100 MW. Line trip should not increase the current more than 120% of the rating for the neighboring lines. All buses under 154 kV are reviewed for transmission overload, the necessity of additional substation expansion, overcurrent, and transient analysis.

In step 3, the capacity able to be interconnected by region of grouped peripheral substations is reviewed. The grouping of meshed and radial networks is initiated, which then expands to grouping by regions in close proximity. The rest of the process is the same as that in step 2 but at the 345 kV level.

As the overall scale of the power system steadily expands, the fault current of the system also increases. KEPCO has been working with various power companies to discuss the use of circuit breakers with larger capacities and methods of separating substations. The replacement of circuit breakers with those of larger capacities requires high capital investment, whereas substation separation causes higher power loss owing to impedance increase as well as the overload of transmission capacity. With this condition and status, the influence and impact of fault current contribution can be accurately determined to interconnect renewable generators to the grid without encountering critical problems.

The overcurrent criteria in Korea state that all 154 kV lines and an overcurrent that exceeds 50% of a rated current of a 345 kV line need to be monitored. To simulate the most serious contingency, the fault is applied directly to the bus rather than to the line directly connected to the bus. The bus fault clears after five cycles (approximately 0.0833 s) because of breaker operation. Generators may need to be removed to protect them in case of faults, and the generation dropout rate is estimated to ensure transient stability. Fault current rises as well if additional lines or generators are newly interconnected to the power system, and fault currents exceeding the breaker capacity (50 kA) can lead to secondary impacts. Based on three-phase faults, the fault current is calculated by using PSS/e while all generators are in-service to simulate the most serious phenomena. Based on this analysis, planning can begin for various types of grid reinforcement such as leveling the transmission level, constructing additional transmission lines, or installing larger transformers.

According to the present power system reliability and power quality maintenance standards in Korea, the voltage should be kept within the maintenance range, which is shown in Table 3. When a contingency occurs, the stability maintenance standards must be followed depending on the type of contingency. In the case of a double circuit outage in a radial system, temporary regional load shedding is allowed, but a large-scale blackout must be prevented to meet the requirements

Table 3
Voltage criteria in the Korean power system.

Category	Peak load	Off peak load
Steady state	765 kV: 765–800 kV	0.98–1.02 pu
Steady state	345 kV: 345–360 kV	0.98–1.02 pu
Steady state	154 kV: 154–164 kV	0.98–1.02 pu
Transient state	Upper limit: Same as above	0.98–1.02 pu
Transient state	Lower limit: 0.925 pu	0.98–1.02 pu

for maintaining the security of the system. Therefore, the Korean reliability standard distinguishes between the main system and the radial system according to the voltage level reflecting the characteristics of the system. The allowable range is defined by considering the influence of the contingency affected by each type of fault. In the case of metropolitan areas such as Seoul, the transmission lines are composed mainly of underground cables. Because the probability of cable failure and its impact from a fault differ from those of overhead lines, it is necessary to determine the standard for each line type to refine the overall reliability standard.

4. Early stage of developing renewable energy map

A project for predicting the effective capacity of renewable energy has been undertaken in the areas of interest for interconnection. To study the possible impact of the introduction of renewable generation on the Korean power system, a valid prediction of the effective capacity of the projected renewable generators is required. Various transmission planning entities have used time series methods on accumulated data to forecast the power outputs of renewable generators [54]. To compensate for a lack of data owing to the short history of renewable energy operations in Korea, the project used a spatial modeling technique to analyze two-year data of neighboring renewable generators.

Spatial modeling is a technique used to analyze physical phenomena and data within a certain space and is widely used in various engineering disciplines to predict specific parameters by using topological, geometric, or geographic information. Unlike traditional time series methods, spatial modeling techniques can be useful even when a large amount of accumulated data is not available. This allows researchers to conduct studies on renewable plants that are not yet interconnected.

The research team used variogram analysis along with the Kriging method to predict the capacity factors of the location of interest [55]. The variogram is a function that describes the stochastic dependency between observed variables based on geometric parameters. For each function produced by the variogram, the Kriging method is used to calculate the capacity factor at the location of interest. The Kriging method, a computational method widely used in spatial analysis and computational experiments, derives the best linear unbiased prediction of neighboring values by using a distance-weighted average.

Although three years of hourly output data are available for 60 wind plants and 69 photovoltaic plants operating since 2013, the capacity factors of renewable plants at the location of interest are calculated by using the variogram and Kriging methods, as shown in Fig. 11 [26]. The research team forecasted wind and PV plants for six areas of the Korea power system for each month. In the Gang-won area, which is expected to host the largest number of wind plants in the near future, the maximum capacity factor was estimated as 48.5% in December and 25.2% in August, which is the maximum loading period of the Korea power system. For PV plants, Gang-won and Chung-chung recorded a maximum 40% capacity factor in March, although the entire area was 35% above the capacity factor in April. In August, the capacity factor for all areas varied from 28.8% to 31.7%. Detailed results are shown in Fig. 12 [26].

After the capacity factors were calculated, a study on the impact of aggregated renewable plants was conducted [26]. In addition, a

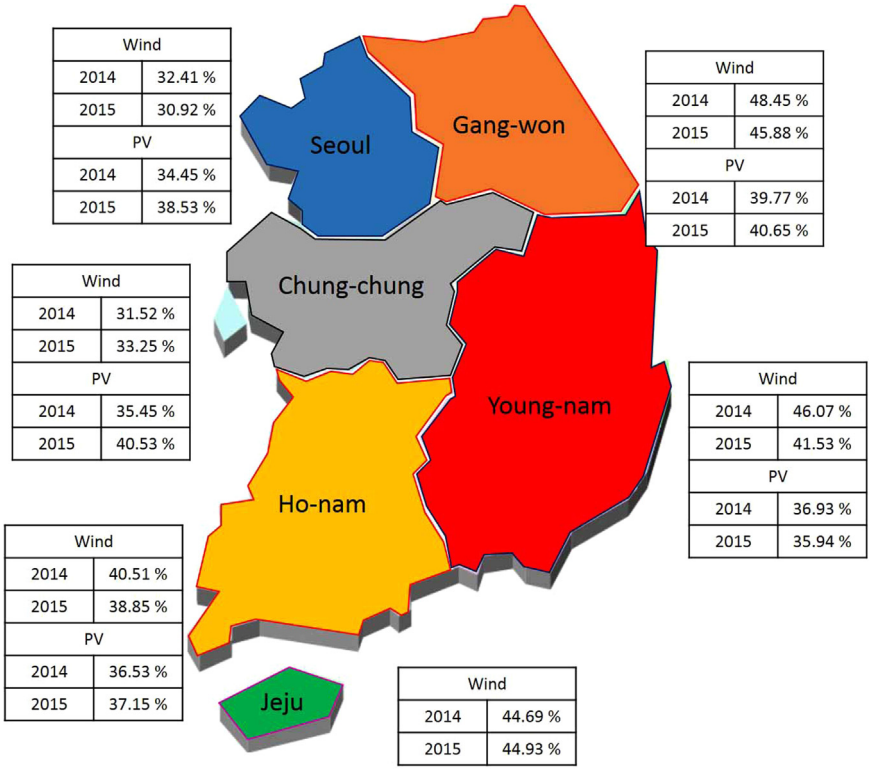

Fig. 11. Estimation of capacity factors in different regions in Korea through variogram and Kriging analysis.

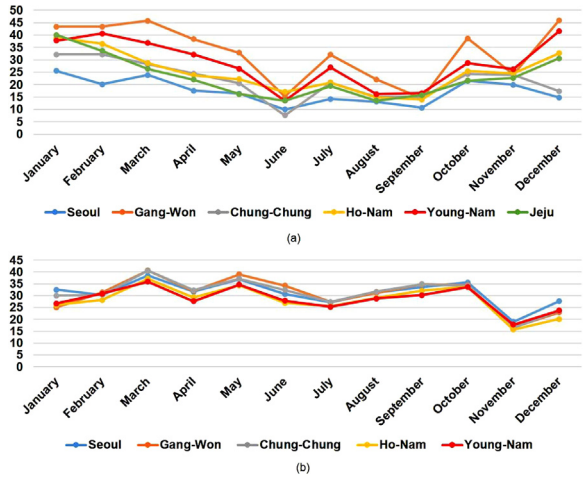
January February March April May June July August September October November December
Seoul Gang-Won Chung-Chung Ho-Nam Young-Nam Jeju
(a)
(b)

Fig. 12. Capacity factor forecast for (a) wind plants and (b) PV based on data of 2015.

prototype of an REM based on PSS/e and Python was developed. As shown in Fig. 13, the program utilizes four stages for hosting capacity assessment. Once the capacity factors and substation capacity assessment mentioned in previous section are processed, certain parameters are input to the program that automatically investigates the hosting capacity, as shown in Fig. 14. These parameters include the renewable plant rating, voltage level of interconnection point, capacity factor, fault current contribution rate, rating and impedance of the transformer, and expected location.

The fault current calculation of renewable plants is conducted on the basis of user input, as previously mentioned. The fault current participation parameter is the percentage of fault current to the rated current. As both wind plants and photovoltaic plants are assumed to be converter-based generators, the fault current varies from 120% to 150% of the rated current. To reflect this situation, the user can designate the level of fault current participation for each planned renewable plant. All of the renewable plants are assumed to have their maximum capacity factor forecasted.

An example of input data is shown in Table 4. In this case, a total of 1100 MVA of wind power plants (type 4) are interconnected into potential hubs located in southwestern, southeastern, and eastern Korea. Each of the plants has a rating of 100 MVA with different capacity factors based on the location. The developed automation program can read detailed information on renewable plants and automatically conduct a limit check and an $N-1$ security study for all connected transmission lines, as stated in analysis zone in Fig. 13. If the case does not violate the reliability standard, the margin for error can be checked. The accuracy of the capacity factor determined by the aforementioned method is low because the history of data accumulation is very short. Therefore, the capacity factor must be increased as a conservative approach. Finally, the program automatically scans and produces reports for any transmission overload and voltage limit violation based on the reliability standard of the Korea power system.

The current status of the REM program is still a prototype in which the system security is screened when the aggregated renewable plants are interconnected in various locations. The development of this automation tool has reduced the time and effort needed for studying the impact of new renewable plants, which allows power system planners to easily conduct preliminary studies on different network and generation plans. This tool will be further developed to produce the report and a visual map that presents consolidated information of the current and future capacity of the power system by regionally and specific buses, as shown in Fig. 15. This will help to prevent overestimations of the expected facility interconnection as well as unnecessary restricted generation of renewable plants.

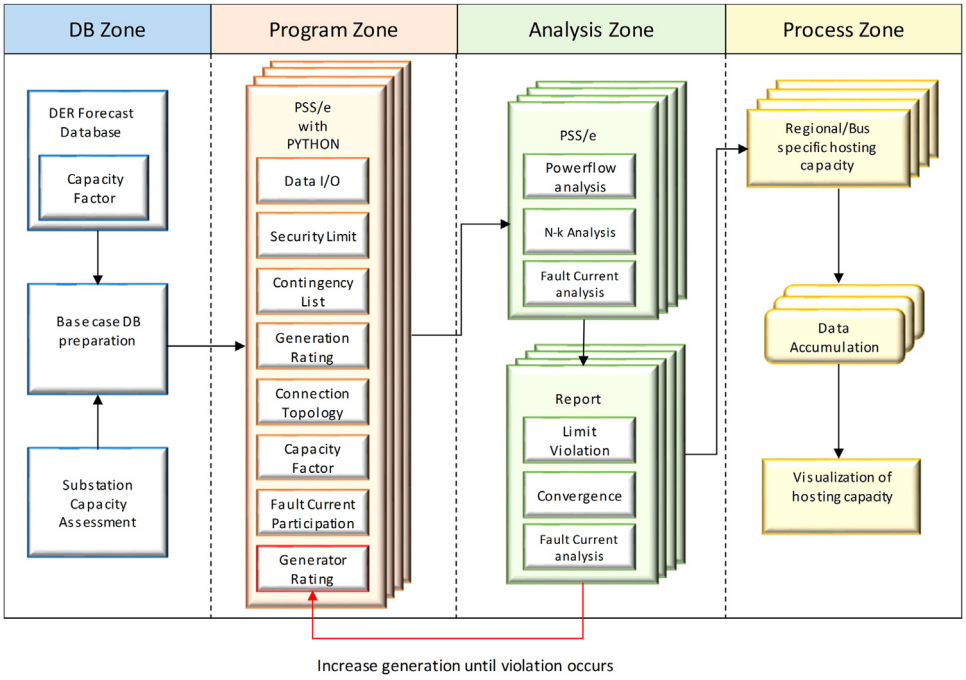

Fig. 13. Procedure for analyzing hosting capacity and system impact on the power system using the developed program.

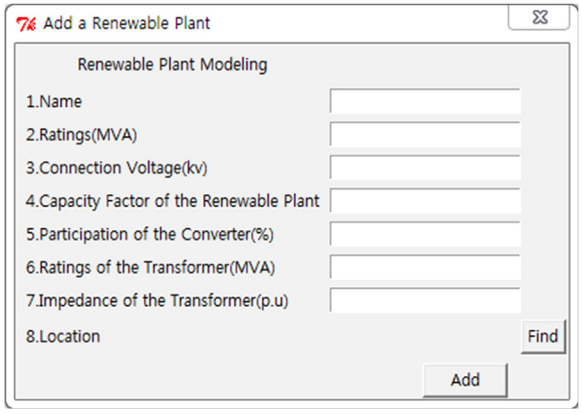

Fig. 14. Input section of a prototype REM program for automated screening operation.

5. KEPCO's vision to expand renewable penetration efficiently

5.1. Various active projects for renewable energy aggregation

Although the prototype of the REM must undergo major upgrades, a well-developed REM will help in realizing the vision presented by KEPCO for proactive renewable integration. KEPCO has proposed the "G-platform" project, which offers opportunities to different renewable plant companies to interconnect with compact substations for stable and efficient aggregation (Fig. 16) [22]. As shown in Fig. 17, KEPCO envisions regional renewable interconnection planning to effectively support regional loading through the establishment of 70 kV compact modular substations [5].

As shown in Fig. 18, KEPCO is developing a remote monitoring and operating system alongside an exclusive renewable power conversion system to mitigate power system constraints, forecast renewable energy generation, and enhance power quality [22]. This strategy ensures the reliability and maintenance of the power system and quality in the case of contingency.

Efforts for increasing an offshore wind farm have been initiated. Although Saemangeum, in southwestern part of Korea, has abundant wind power resources, a project to develop a massive offshore wind complex has also begun [5]. The government and KEPCO envision a 2 GW offshore wind farm by connecting the main land with HVDC. Currently, a 100 MW offshore wind farm is being constructed and is at the feasibility stage, generating 210 GWh per year. The planned increase in capacity of the farm is 400 MW at the demonstration stage, which will generate 1096 GWh per year and will help in a acquiring track record for developing a business model. Finally, the capacity of

Table 4
An example input data for REM program.

Area	Capacity (MVA)	Voltage (kV)	Capacity factor (%)	Fault current participation (%)	Transformer rating (MVA)	Transformer impedance (pu)	Bus number
Southwest	100	10	20.0995	120	60	0.26667	6445
Southwest	100	10	20.1869	120	60	0.26667	7340
Southeast	100	10	24.6698	120	60	0.26667	8980
Southeast	100	10	24.6441	120	60	0.26667	8990
Southeast	100	10	24.6478	120	60	0.26667	8975
East	100	10	33.9568	120	60	0.26667	5670
East	100	10	34.2839	120	60	0.26667	5680
East	100	10	34.454	120	60	0.26667	5695
East	100	10	40.4425	120	60	0.26667	5780
East	100	10	42.3312	120	60	0.26667	5925
East	100	10	34.9561	120	60	0.26667	5895

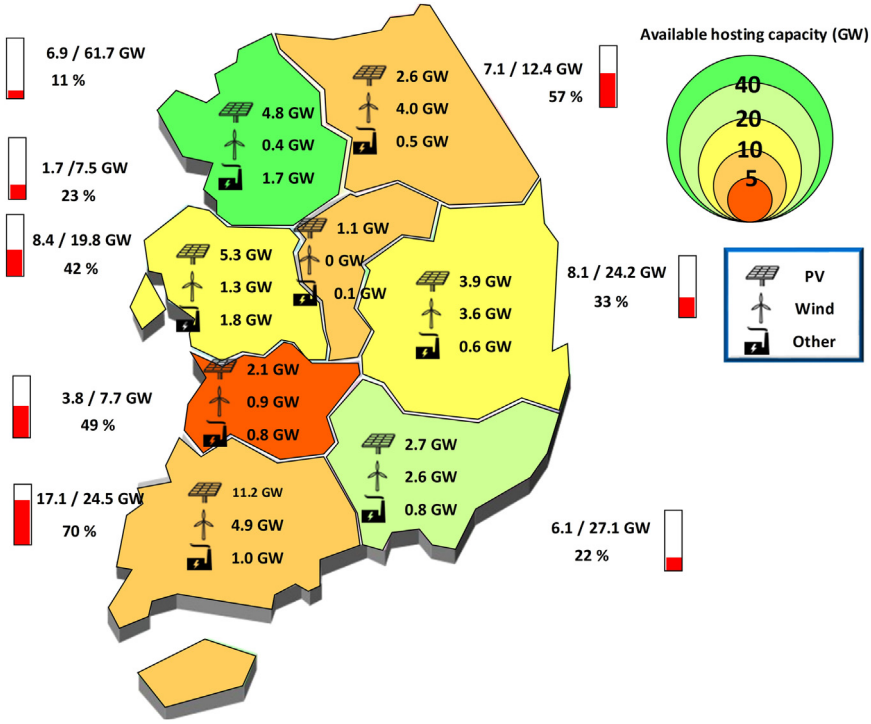

Fig. 15. Visual results of hosting capacity for renewable plant interconnection in the Korea power system.

the wind farm will be increased to 2000 MW by 2023, which will generate 5219 GWh per year [5]. Currently, delays have occurred in this project owing to constraints on military facilities, sea routes, and environmental protection zones. However, the government has eased regulations according to its goal of expanding renewable sources.

5.2. Monitoring system for 3020 project

Currently, a real-time renewable energy integrated monitoring system is operating that collects data on the amount of energy generated and the malfunction status regionally by analyzing the inclination angle and condition of modules and inverters. However, this system does not show the status of the power system network. The government and KEPCO have invested $55 million to install 12,000 remote terminal units (RTUs) and correlate the communication network nationwide to more accurately collect detailed data that can be utilized for power system analysis [5]. Through improvement of the reliability of data by standardizing the different measuring cycles and communication protocols, it is possible to cope with the expected voltage instability and power fluctuation more accurately and quickly. Starting from the southwestern region, where the most renewable sources will be aggregated, a total of 14 system operation centers will be in place to monitor and operate the renewable complex. The centers will be on pilot operation for two years and will be in complete operation in 2020. In addition to monitoring and predicting the real-time output of renewable sources, the system operation centers will also control the output in the case of contingency.

5.3. "Carbon Zero" island project on Jeju

5.3.1. Wind power generation in Jeju

Jeju Island is located in southern Korea, and its power system is totally contained on the island, as shown in Fig. 19. Because of the availability of wind energy sources, Jeju Island has been designated as a zero carbon project with large-scale wind power implementation; its peak load was approximately 912 MW in 2017 [5]. This massive wind power penetration surpasses the peak load of Jeju Island and requires power transmission back to the mainland power system, as shown in Fig. 20. Two line-commutated converter (LCC) HVDCs of 300 MW and 400 MW, respectively, are currently delivering power to Jeju from the mainland. Approximately 273 MW of the wind farm is in operation; KEPCO has proposed that the capacity of the wind farm will reach 2 GW by 2030 [7,21]. Because the power generated in Jeju will surpass the load demand, the rest of the power will be sent back to the mainland through the HVDCs. The voltage-sourced converter (VSC) HVDC enables fast power control and continuous power reversal; thus, HVDC

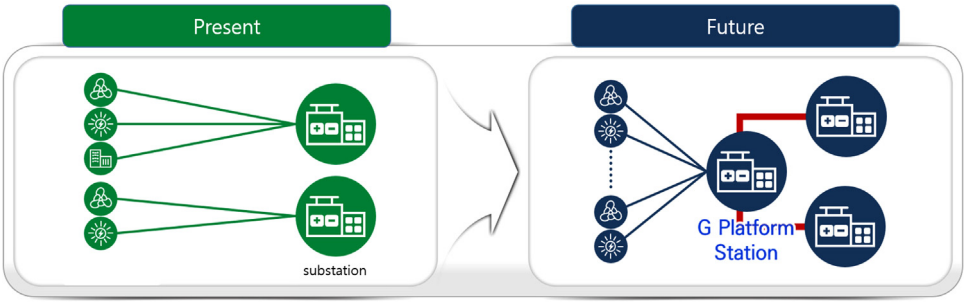

Fig. 16. "G-platform" project for efficient renewable plant aggregation.

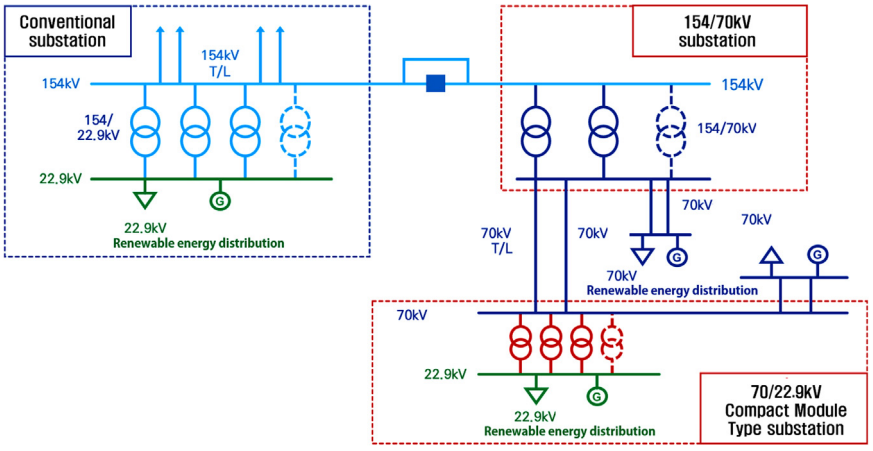

Fig. 17. Regional renewable interconnection planning for effectively supporting regional load by establishing a 70 kV compact module substation.

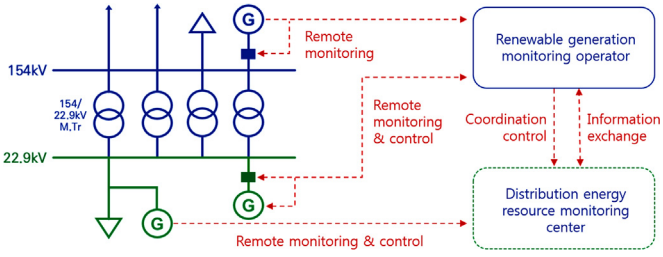

Fig. 18. Remote monitoring and operating system with exclusive renewable power conversion system.

No. 3 (200 MW, under planning; [5]) is expected to become a VSC.

5.3.2. Development of a renewable monitoring system in Jeju

In addition to wind power, Jeju also generates PV. Approximately 121 MW of the PV farm is in operation, and the total PV capacity is expected to be 300 MW by 2030 [7]. In 2030, renewable (wind + PV) generation in Jeju is expected to reach 2.3 GW. The increase in penetration level of renewable energy implies an increase in the converter based technology in the power system. This might threaten the security and stability of the power system. Thus, KEPCO is developing a renewable monitoring system in Jeju. A communication network and infrastructure will be developed for the system monitoring wind power, PV, and ESS. In addition, online renewable power generation forecasting and a grid security and stability analysis program will be developed. The project will be completed in 2019 and will also be applied to the main grid after its completion. KEPCO expects that the project will improve stability, security, and reliability in the future power system environments where the penetration of renewable energy is high.

5.3.3. Future grid requirement for reliable and secure power grid on Jeju

The Jeju power system requires high operation coordination between HVDC and renewable energy to comply with the grid code for both the mainland and the Jeju system. When the Jeju power system is highly condensed with converter technology, the effects will be uncertain because not many countries have encountered this issue before. Because inverter-based distributed energy sources are not able to provide inertia and reactive power, severe frequency and voltage stability problems are likely to occur because the penetration level of wind power generation is growing rapidly. Advanced inverter technology with a communication network may be required for renewable energy generation. The advanced inverters can support synthetic inertia and reactive power, which contribute to grid reliability, resiliency, and

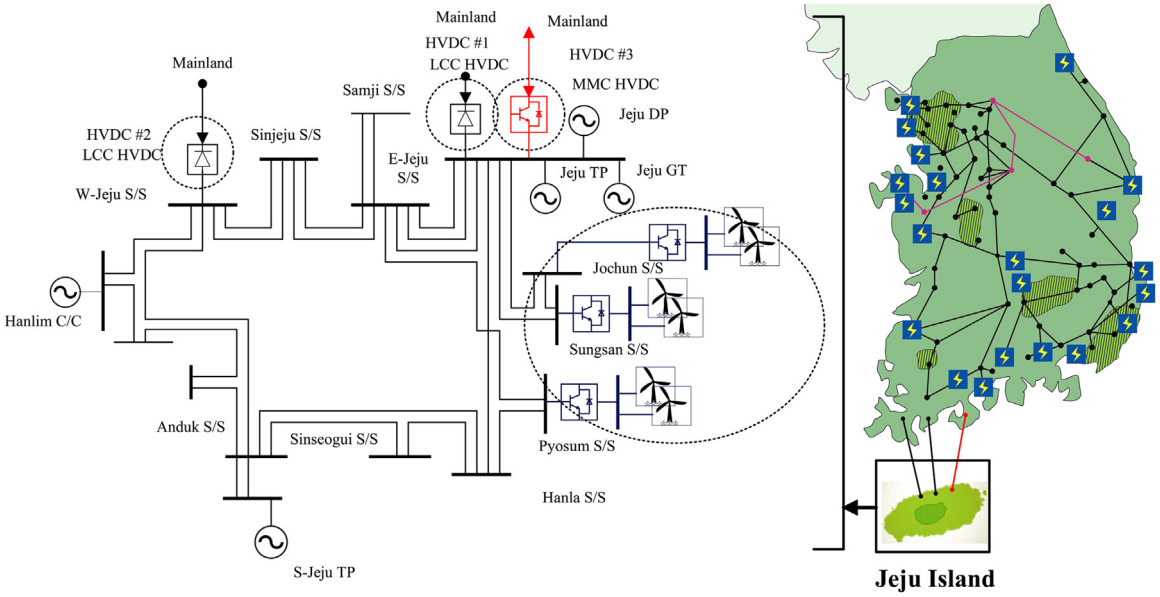

Fig. 19. Simple representation of the Jeju power system.

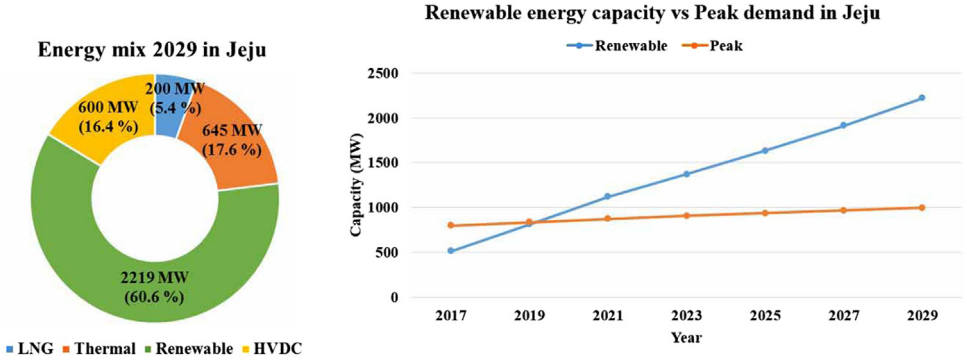

Fig. 20. Renewable energy proportion and renewable energy capacity expected by 2030.

security. Therefore, the positioning of renewable generation is important when determining the most effective contribution of synthetic inertia to the Jeju power system. HVDC No. 3 may play the most important role in stabilizing the Jeju power system and in increasing the hosting capacity. Thus, explicit research is required on grid services in terms of maintaining the stability and quality of the power system. The results can be used to address the issues faced during operation of the power system based on power electronics and for pursuing the "Carbon Zero" island goal in Jeju.

6. Conclusion

Currently, Korea is undergoing major renovations of the power system infrastructure by increasing the penetration of renewable energy to reduce carbon dioxide emissions. The government has proposed a mission to reduce carbon dioxide emissions by 37% from the BAU value. The government has supported this vision financially by providing subsidies on installation costs and by redesigning a market structure that is not solely dependent on the SMP price. The interconnection duration should be shortened to fulfill its guaranteed interconnection policy of renewable energy sources under 1 MW. In line with these initiatives, KEPCO has begun to perform comprehensive preliminary studies to evaluate the hosting capacity for renewable energy sources and has offered a plan for reinforcing the grid proactively. Efficient integration provides higher efficiency and environmental friendliness and also mitigates the capital investment for grid reinforcement. An automated screening tool for the REM has been developed to facilitate renewable energy impact studies. For renewable energy sources of interest, the credible capacity factors and fault current contributions are incorporated for more practical study results. This REM should help KEPCO to conduct proactive network expansion planning and to unlock the benefits of renewable energy sources. KEPCO will also provide "G-platforms," or substations at strategic locations to support renewable energy integration. By taking advantage of the weather on Jeju Island, plans are under way to make the island carbon-free by 2030. Although Jeju's power system may be vulnerable to instability owing to the large penetration of wind sources that lower system inertia, smart converter technologies will play a major role in stabilizing the frequency and voltage and in controlling power flows. Improvements in preliminary study methods, support schemes from the government, proactive interconnection procedures, and power system planning will together ultimately advance the renewable energy market in Korea. These experiences will provide insight and an attractive base for application to other countries as well.

Acknowledgements

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